Origins of the Kuroshio and Mindanao Current

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LONG-TERM GOALS

The boundary currents off the east coasts of the Philippines and Taiwan are of critical importance to the general circulation of the Pacific Ocean. The westward flowing North Equatorial Current (NEC) runs into the Philippine coast and bifurcates into the northward Kuroshio and the southward Mindanao Current (MC). Quantifying these flows and understanding their dynamics are essential to improving predictions of regional circulation, and to characterizing property transports that ultimately affect Pacific climate. Fluctuations in the Kuroshio and MC can significantly impact variability downstream. For example, the Kuroshio penetrates through Luzon Strait into the South China Sea and onto the East China Sea shelf. The Kuroshio front dramatically alters stratification and may impact internal wave propagation. OKMC incorporates observation, theory, and modeling to make fundamental advances in our knowledge of the origins of the Kuroshio and Mindanao Current.

OBJECTIVES

The overarching goal of OKMC is to quantify patterns of flow and fluxes of mass, heat, and salt, for the ultimate purpose of establishing predictability. We have three major research themes in OKMC:

- Transport and flow patterns
- Temperature/salinity properties and modifications

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- Eddies and their effect on mean flow

This report covers contributions to these themes from several efforts at Scripps Institution of Oceanography. These efforts include the deployment of underwater gliders, drogued drifters, and profiling floats, and the use of forward and assimilative models. Specific objectives include:

- Establish the regional mean and variability of currents and water properties
- Identify fine-scale variability and its connection to regional properties
- Distinguish the effects of local and remote forcing on the origins of the Kuroshio and MC
- Provide targets for studies of predictability

APPROACH

The proposed observing system employs a suite of complementary platforms to meet the challenges posed by this vast, highly variable study area. Guided by previous studies and by directed analysis of historical data, long-endurance autonomous gliders are tasked to collect repeat occupations of key sections across the NEC, MC. Drifters and floats are used to illuminate the pathways by which the NEC ultimately forms the Kuroshio and MC. Numerical approaches aid interpretation and explore the predictive capabilities of regional models.

WORK COMPLETED

Gliders

Gliders are being used to observe the NEC and the Mindanao Current. Two Sprays are deployed from Palau every 4-5 months, one that proceeds northward across the NEC, and one that heads westward towards the MC. Operations commenced in June 2009 and have continued uninterrupted. The data set includes 24 glider missions. To date, we have completed 21 crossings of the Mindanao Current, and 20 sections across the NEC (Figure 1). In total, the gliders did over 12,000 dives, and covered over 53,000 km in 3000 days. The final recovery occurred in January 2014.

Analysis to date has focused on the NEC for two reasons. First, the NEC is more observationally tractable, as the glider is able to make relatively straight and repeatable sections. Second, and more importantly, the NEC provides the inflow condition for the region. Thus, many of the other components of OKMC focused on the Kuroshio benefit from knowledge of the NEC. The mean geostrophic velocity from the glider sections shows a clear pattern of westward flowing NEC in the upper ocean, with cores of eastward undercurrents below. The base of the NEC deepens to the north, in rough correspondence with the slope of potential density surfaces. Two cores of undercurrents are apparent at about 9.5°N and 13°N, each about 1.5° wide. These NEC undercurrents are a newly discovered feature, constituting one of the first fundamental results of OKMC (Qiu et al, 2013, GRL). The undercurrents dominate variability of the upper 1000 m transport; when the undercurrents are strong they can cause the transport to vanish or be locally eastward.

Mean salinity calculated from all sections shows two clear extrema associated with the prominent water masses in the region. A salinity maximum near 150 m (23.5 kg m^{-3}) runs down the center of the section in the NEC. This salinity extremum, sometimes called North Pacific Tropical Water (NPTW), is seen throughout the region, carried by all the major currents. Quantifying the path and evolution of NPTW provides a means to tie together OKMC measurements in different locations, and serves as a

target for modeling and prediction. A salinity minimum exists near 500 m (26.5 kg m^{-3}) at the north end of the section. The salinity minimum, the well-known North Pacific Intermediate Water (NPIW), lies mostly beneath the major currents so it spreads relatively slowly. Glider profiles are separated by about 6 km, so they allow an examination of the submesoscale. This variance is largest on the isopycnals corresponding with salinity extrema, that is in the NPTW and NPIW water masses. The submesoscale variance is weakest in the region between the water masses. This pattern is quantified using wavelets to isolate variability at wavelengths shorter than 50 km. Variance calculated on isopycnals is clearly largest in the salinity extrema, implicating isopycnal stirring processes as the cause. A horizontal Cox number has been calculated as a ratio between salinity variance at wavelengths shorter than 80 km to variance at scales longer than 120 km. This Cox number of order unity and is remarkably uniform as a function of density. This uniformity support the notion that the submesoscale variance is caused by stirring of the large scale salinity gradient.

Graduate student Martha Schonau is supported by an Early Student Support (ESS) grant, and her doctoral research is focusing on Spray glider data from OKMC. She successfully advanced to candidacy for a PhD in June. She is nearing completion of a manuscript “Glider observations of the north equatorial current in the western tropical Pacific” for submission to JGR. The remainder of her thesis will focus on glider observations in the Mindanao Current, and on comparison of glider data with the OKMC numerical models funded by this grant.

Floats

Ten floats were deployed in August 2011 from the Japanese R/V Mirai. Data from these floats are processed through the Argo system, and are made available through GTS to modeling centers including NAVO. An additional 17 floats obtained through a DURIP were deployed in March 2013 from the R/V Mirai. Of the 27 floats deployed, all but one returned data. Analysis of these data is in collaboration with Bo Qiu of U. Hawaii, with the first publication addressing distinct cores of undercurrent beneath the NEC (Qiu et al., 2013).

Drifters

To enhance the historical near surface current data in the study area, deployments of surface drifters from the merchant vessels from Kaohsiung to eastern Australia were performed. The deployment locations were chosen from the analysis of the historical drifter dataset in order to sample the seasonal variability of the flow at the roots of the KC and of the MC. Professor Ruo-Shan Tseng at National Sun Yat-sen University was local contact point in Taiwan to store, prepare and deliver the drifters to the ship. The drifter deployments were completed in 2013. In total, we have deployed 268 SVP drifters (Figure 1) in the OKMC region from August 2010 through August 2013 (255 from VOS and 13 in Lamon Bay from the R/V Revelle).

The drifter data were first quality controlled and a kriging interpolation routine was then applied to obtain 6 hourly, regularly spaced, drifter location time series from which the drifters’ velocities were obtained. A wind slip correction was also applied and the velocity data from drifters that had lost their drogue were recovered. The drifter data were analyzed using standardized techniques published in the peered reviewed literature to compute the Lagrangian statistics, the mean surface velocity field the eddy kinetic energy (EKE) and the unbiased geostrophic surface flow obtained from a combination of drifter, wind and satellite altimetry. Other dynamically important quantities such as the acceleration the drifters along their track, whose curl corresponds to the divergence of the mean and eddy vorticity fluxes, and the mechanical energy exchange between the mean flow and the eddies were also computed. Main results are as follows:

- the surface expression of the MC intensifies at the same location (~11N, 126,5E) throughout the year.
- the location at which the KC intensifies changes seasonally and, on average, is located at 17N 122.5E during the NE monsoon and shifts southward as far as 13.45N 124.5E during the SW monsoon.. The current system feeding into the nascent Kuroshio of Lamon Bay was also studied. During the time of observations it was bracketed by an anticyclonic dipole to its northeast and a cyclonic dipole to its southwest.
- A well-defined surface connectivity between the MC and the NEC occurs year-round as shown by the large (1 m/s) speeds of drifters that from the NEC drift into the MC.
- The surface velocity of the KC also shows a well-defined seasonal cycle at 15.5N, 123.5 E, consistently with the seasonal changes, namely a wintertime increase, of the horizontal gradient of the sea level at the origin of the boundary current, as required by geostrophic adjustment.
- The decadal strengthening of the negative wind stress curl and trade winds in the subtropical area north of Hawaii and west of 150E are the driving forces of the decadal variability of a recently discovered wintertime westward current that occurs between 18N and 23N.
- The mechanical energy exchange between the mean flow and the eddies computed from the drifter data suggests a possible transfer of energy from the eddies to the mean flow in the KC and MC origin regions.

Modeling
The MITgcm 4D-Var state estimation using satellite SSH and SST, and with temperature and salinity profiles from floats and gliders has been run through two years (2010 - 2011) in one month segments. The optimized state from the end of the each segment was used to initialize a forecast for one month using climatological forcing, open boundary conditions, and run-off fluxes. Each monthly state estimate and forecast has been compared to observations to assess the model performance against each of them, and we are now adjusting some of the model parameters to refine the state estimates. In particular, the viscosity of the adjoint model has been significantly reduced to increase the model performance near the end of the hindcast periods. Maps of SSH prediction error for different forecast periods have been constructed and show that the state estimate improves the forecasts of SSH near the Philippine coast, where it is expected to influence the boundary transport. We also constructed a composite map of SSH prediction error from all monthly forecasts and show that the prediction error increases over time as expected. We have checked the non-assimilated model simulations and the state estimates against the mapped Argo data from Gilson and Roemmich to look for biases in salinity on isopycnals, and found that there are no large offsets. The maps of salinity on isopycnals for assimilated and non-assimilated model solutions are also useful for examining water mass variability in collaboration with Martha Schonau and Dan Rudnick.

We are in process of writing up the forecast skill and the results from sensitivity calculations for the 1/6 degree regional domain of the Northwest Pacific Ocean, which has significant nonlinearity in places. The state estimates for the OKMC region are being compared against estimates and sensitivities in the Philippine Sea, which is much more strongly nonlinear but still shows good hindcast and forecast performance.

Mesoscale eddies propagate westwards from the interior of the Pacific Ocean to interact with the KC. To study the importance of eddy forcing on the mean KC flow in this region, we used a full vorticity

budget calculated from output from an eddy-active (1/10°) global ocean general circulation model: the Parallel Ocean Program (POP), forced with synoptic interannually varying reanalysis atmospheric fluxes. A decomposition into a time mean and time variable or eddy component was applied, allowing us to evaluate the relative importance of the two eddy forcing terms on the mean flow terms. To compute the budget, extra quantities were needed from POP that are not typically archived, so we needed to rerun from an existing spun-up POP state for 2005-2009. The budget was then constructed over the upper water column using only interior ocean points to avoid sidewall pressure torques. These calculations were conducted on both an annual and seasonal basis. We are in the process of writing up these results for publication. Study of the variability of the deep undercurrents as depicted by POP in the NEC and their relationship to deep western boundary currents off the Philippines is continuing.

RESULTS

Our most important results are as follows:

- The mean NEC is firmly established, with the strongest flows in the south and near the surface. Eastward flowing undercurrents are robust features that dominate variability of upper 1000 m transport.
- The salinity maximum of the North Pacific Tropical Water is a useful tracer throughout the region. An examination of submesoscale variance in the region supports the notion of stirring of a large scale salinity gradient.
- Predictability of the SSH near the boundary using the state estimate has skill greater than persistence at time lags of a few weeks.
- The sensitivity of SSH and transport to wind stress curl spreads to the east going backwards in time, but advection is important. The influence of the model state on the gradients (nonlinearity) is more apparent at these shorter scales, and nonlinearity clearly increases poleward. The contribution of the coastal waveguide is smaller than that of the propagating Rossby waves, but it is still important, and points up the relation to island rule theory and its generalizations.
- Simulated eddy-mean flow interactions as represented by eddy forcing terms on the mean flow terms in a full vorticity budget using POP output showed eddy vorticity forcing to occur around the northern tip of the Philippines, in the Luzon Strait, and to the east of Taiwan. Seasonal analyses show that the magnitude of this forcing varies such that the highest values occur in spring while the lowest occurred in fall.
- POP simulates deep permanent eastward flowing subsurface jets (~500-1000 m depth) at 9.5°N and 13°N along 134.5°E; core mean speeds are roughly 2 cms^{-1}. It also simulates deep western boundary currents flowing from the north and south along the Philippines, which form an offshore confluence in this latitude band and at these depths. A contiguous eastward current is seen to flow across 134.5°E, contributing to the flow in these deep jets.

IMPACT/APPLICATIONS

- The demonstration of glider utility in a strong western boundary current should influence future glider operations in similarly strong flows. Gliders have shown proven ability for the sustained observation of major ocean currents. All glider data is being sent to NAVO in real time.

- The value of drifters for regional oceanography is being further established through this program. All the drifter data were posted in real-time to the Global Telecommunication System of the World Weather Watch.
- The boundary current region is tractable for model analysis and prediction based on ocean state and atmospheric forcing.

RELATED PROJECTS

Related projects include an ongoing Early Student Support grant and a completed DURIP. This project takes advantage of glider technology that has been developed through grants from several agencies including ONR, NSF, and NOAA.

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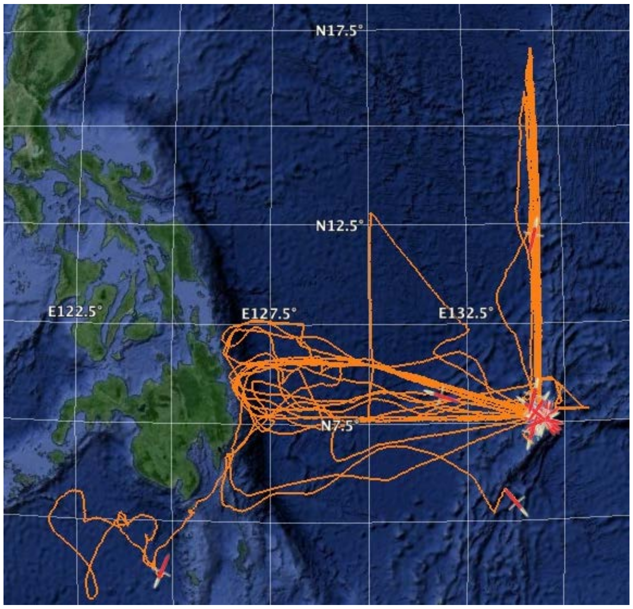

Figure 1. Spray glider trajectories for all missions since June 2009.

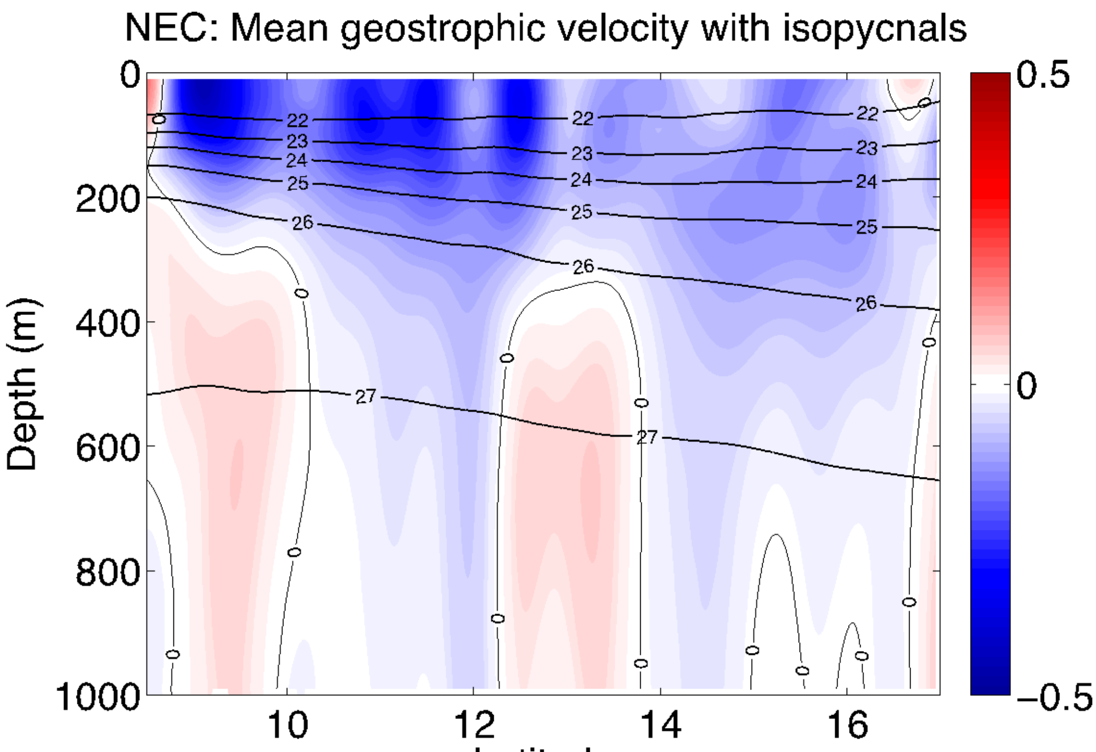

Figure 2. Mean eastward geostrophic velocity from glider sections across the NEC, along 134°20'E. The geostrophic flow is referenced to the depth-average current directly measured by gliders, revealing strong cores of eastward flow below the NEC.

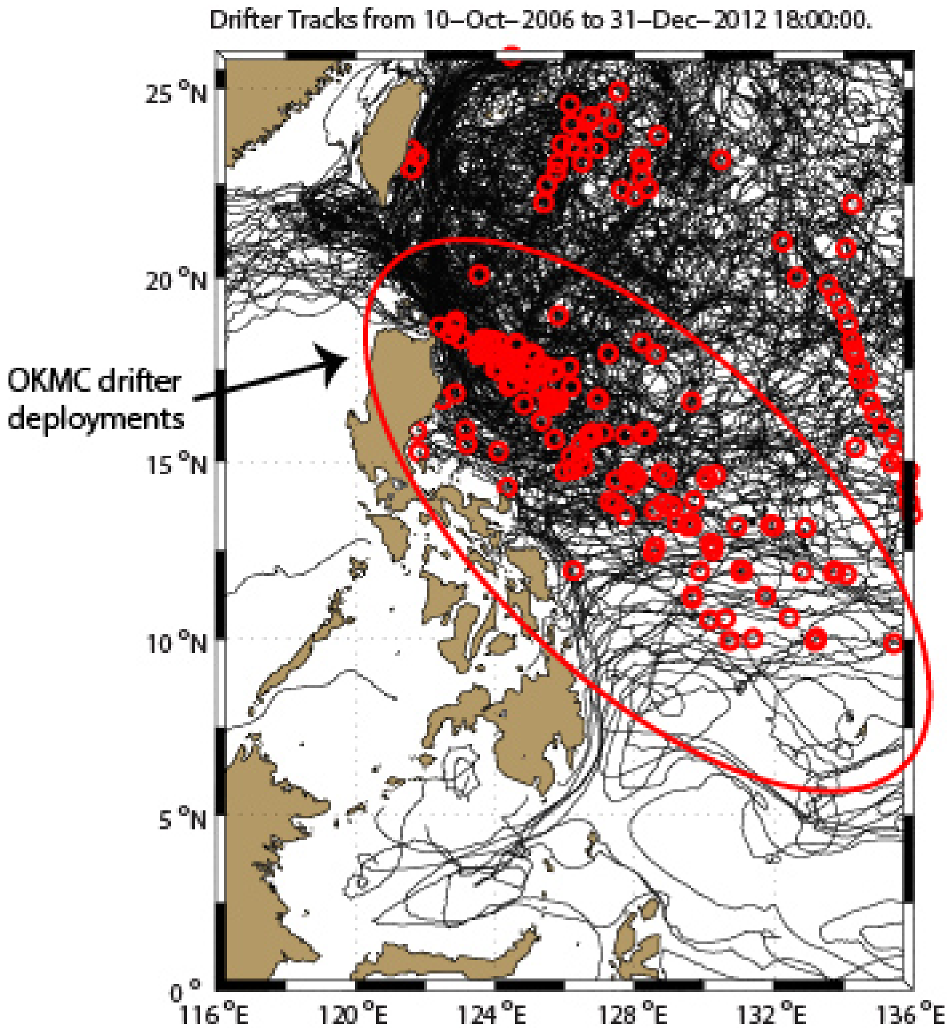

Figure 3. Drifter tracks in the NW Pacific Ocean during the OKMC period. The OKMC drifter deployments for the August 2010-December 2012 period are circled with the red ellipse.